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Greener energy: Issues and challenges for Pakistan—Solar energy prospective

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ABSTRACT

Energy plays a pivotal role in socio-economic development by raising standard of living. It is becoming gradually accepted that current energy systems, networks encompassing every thing from primary energy sources to final energy services, are becoming unsustainable. Development of conventional forms of energy for meeting the growing energy needs of society at a reasonable cost is the responsibility of the Governments. In recent years, public and political sensitivities to environmental issues and energy security have led to the promotion of renewable energy resources. Diversification of fuel sources is imperative to address these issues; and limited fossil resources and environmental problems associated with them have emphasized the need for new sustainable energy supply options that use renewable energies. Development and promotion of new non-conventional, alternate and renewable sources of energy such as solar, wind and bio-energy, etc. are now getting sustained attention. Solar power is one of the hottest areas in energy investment right now, but there is much debate about the future of solar technology and solar energy markets. This investigates the progress and challenges for solar power in Pakistan according to the overall concept of sustainable development, and identifies the region wise potential of solar power in Pakistan and its current status. Barriers are examined over the whole solar energy spectrum and policy issues and institutional roles and responsibilities are discussed.

Contents

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1. Introduction

Solar energy is the most abundant permanent energy resource on earth and it is available for use in its direct (solar radiation) and indirect (wind, biomass, hydro, ocean, etc.) forms. This article is limited to the direct use of solar radiation. Earth receives about 100,000 TW of solar power at its surface – enough energy every hour to supply humanity's energy needs for a year. Theoretically, the world's entire primary energy needs could be served by less than a tenth of the area of the Sahara [1].

Photovoltaic (PV) is an empowering technology that has shown that it can generate electricity for the human race for a wide range of applications, scales, climates and geographic locations. PV technology is proven and easy to use solar of energy to generate electricity. It is being used globally to supply power to remote communities, utility peak load shaving, cathodic protection in pipelines, remotely located oil fields and gas oil separation plants (GOSPs), telecommunication towers, highway telephones and billboard, off-grid cottage/s, resorts in desert areas, water pumping for community and irrigation, municipal park lighting, exterior home lighting and many other usage. Standard commercial solar PV panel can convert 12–18% of the energy of sunlight into useable electricity; high-end models come in above 20% efficiency [1]. Increasing manufacturing capacity and decreasing costs have led to remarkable growth in the industry over the past 10 years.

PV can often be installed piecemeal – house by house and business by business. In these settings, the cost of generation has to compete with the retail price of electricity, rather than the cost of generating it by other means, which gives solar a considerable boost. The technology is also obviously well suited to off-grid generation and thus to areas without well-developed infrastructure. The public accepts solar technology and in most places approves of it – it is subject to less geopolitical, environmental and aesthetic concern than nuclear, wind or hydro, although extremely large desert installations might elicit protests [1]. With the policies of many countries in promoting the PV solar cell industry, the industry has grown tremendously, and the global production capacity of silicon solar cell increased from 52 MWp in 2000 to 12.0 GWp in 2008 [2]. Even though PV systems can offer cleaner and plentiful energy, the major obstacle they face is that their energy cost is still too high [3]. The most commonly used solar cell today is made from crystalline silicon, but the main trend of solar cell industry is toward the PV silicon thin-film solar cell because of its potential for reducing production costs, low material consumption, lower energy consumption and a shorter energy payback time [4].

Pakistan is estimated to possess a 2.9-TW solar energy potential. PV units have been installed in mosques and schools and used for solar lanterns, solar home light systems, street and garden lighting and telecommunications. Country has a large number of remote villages that do not have electricity supplies. Linking the rural areas to national electricity grid would be very difficult because it would need a lot of time and budgetary investments. However, solar energy technologies might be the lower cost options in rural Pakistan's villages, where population and load density are low. Serving both as an infrastructure and input, the positive contribution of electricity to the Human Development Index is strongest for the first kilowatt-hour reflecting that the poorest are most likely to benefit from even minimal electricity inputs [5]. Rural electrification is also one of the key drivers in achieving millennium development goals (MDGs) as it facilitates economic and socio-cultural development of the target population. The problems of high transmission and distribution (T&D) losses; frequent disruption in supply of grid power, practical difficulties and financial un-viability of extending grid to remote and inaccessible areas, etc. are plaguing the rural electrification program in Pakistan. Off grid electrification have proved to be the viable solution for providing electricity in remote areas such as islands, hilly regions and similar remote areas, where grid extension is economically not feasible. In India large number of remote areas in the country that have been electrified with renewable energy technologies have made a visible impact in the quality of life of the people inhabiting in these areas [6]. Research and development of solar thermal devices is being undertaken by The Pakistan Council of Renewable Energy Technologies (PCRET). Such systems include parabolic/concentrator and box-type solar cookers, solar still for the provision of clean drinking water, and flat-collector and evacuated-tube solar water heaters. One particular area of success has been the introduction of solar dryers to the agricultural areas. PCRET has designed and developed a solar hybrid dryer for processing – on a commercial basis – apricots, dates and other fruits.

2. Solar energy technologies

The following sections will outline existing solar technologies for understanding of each technology and its associated challenges.

2.1. Photo voltaics

PV is the technology that generates direct current (DC) electrical power measured in watts (W) or kilowatts (kW) from semiconductors when they are illuminated by photons. A PV power generation system are rated in peak kilowatts (kWp) which is an amount of electrical power that a system is expected to deliver when the sun is directly overhead on a clear day [7]. Fig. 1 shows the components and schematic of typical Photovoltaic Installation. PV devices are rugged and simple in design requiring very little maintenance and their biggest advantage being their construction as stand-alone systems to give outputs from microwatts to megawatts. Hence they are used for power source, water pumping, remote buildings, solar home systems, communications, satellites and space vehicles, reverse osmosis plants, and for even mega watt scale power plants. With such a vast array of applications, the demand for PVs is increasing every year [7,8].

The solar cell is the elementary building block of the PV technology. Solar cells are made of semiconductor materials, such as silicon which have weakly bonded electrons occupying a band of energy called the valence band. When energy exceeding a certain threshold, called the band gap energy, is applied to a valence electron, the bonds are broken and the electron is somewhat "free" to move around in a new energy band called the conduction band where it

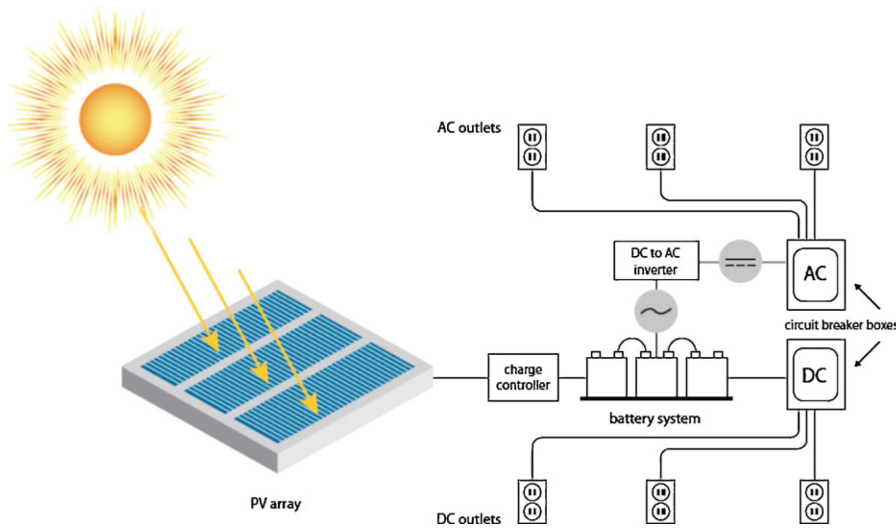


Fig. 1. Schematic of a photovoltaic installation.

can "conduct" electricity through the material. Thus, the free electrons in the conduction band are separated from the valence band by the band gap (measured in units of electron volts or eV). This energy needed to free the electron can be supplied by photons, which are particles of light.

In the fabrication of a PV solar cell, silicon, which has four valence electrons, is treated to increase its conductivity. On one side of the cell, the impurities, which are phosphorus atoms with five valence electrons (n-donor), donate weakly bound valence electrons to the silicon material, creating excess negative charge carriers. On the other side, atoms of boron with three valence electrons (p-donor) create a greater affinity than silicon to attract electrons. Because the p-type silicon is in intimate contact with the n-type silicon a p–n junction is established and a diffusion of electrons occurs from the region of high electron concentration (the n-type side) into the region of low electron concentration (p-type side). When the electrons diffuse across the p–n junction, they recombine with holes on the p-type side. However, the diffusion of carriers does not occur indefinitely, because the imbalance of charge immediately on either sides of the junction originates an electric field. This electric field forms a diode that promotes current to flow in only one direction. Ohmic metal–semiconductor contacts are made to both the n-type and p-type sides of the solar cell, and the electrodes are ready to be connected to an external load. When photons of light fall on the cell, they transfer their energy to the charge carriers. The electric field across the junction separates photo-generated positive charge carriers (holes) from their negative counterpart (electrons). In this way an electrical current is extracted once the circuit is closed on an external load [9].

Solar cells can be categorized into two main groups: wafer type (single crystalline or multi-crystalline) and thin film (a-Si, Cd–Te and CIGS). The former are made from wafers cut from a silicon ingot, and the latter are made by depositing silicon directly onto a substrate such as glass or steel. Wafer-type solar cells dominated 95% of commercial PV market while the remaining 5% were mainly PV silicon thin-film solar cells in 2007 [2]. Because the lack supply of crystalline silicone limits the application of conventional silicone solar cells, three major PV silicon thin film materials, including amorphous silicon (a-Si), polycrystalline (Cd–Te), and polycrystalline $CuIn(Ga)Se_2$ (CIGS), are emerging as significant players [10]. The potential reduction of manufacturing costs, low material consumption, and lower energy consumption accelerate the development of PV silicon thin-film solar cell [11]. However, more than 90% of the solar cells currently made worldwide consist of wafer-based silicon cells. Another important family of solar cells is based on thin-films, which are approximately 1–2 μm thick and therefore require significantly less active, semi conducting material. Thin-film solar cells can be manufactured at lower cost in large production quantities; hence their market share will likely increase in the future. A number of solar cells electrically connected to each other and mounted in a single support structure or frame is called a 'PV module'. Modules are designed to supply electricity at a certain voltage, such as a common 12-V system. The current produced is directly dependent on the intensity of light reaching the module. Several modules can be wired together to form an array. PV modules and arrays produce direct-current electricity. They can be connected in both series and parallel electrical arrangements to produce any required voltage and current combination.

There are two main types of PV system. Grid connected systems (on-grid systems) are connected to the grid and inject the electricity into the grid. For this reason, the direct current produced by the solar modules is converted into a grid-compatible alternating current. However, solar power plants can also be operated without the grid and are then called autonomous systems (off-grid systems). More than 90% of PV systems worldwide are currently implemented as grid-connected systems [9].

When the solar cell is exposed to sunlight of sufficient energy, the incident solar photons are absorbed by the atoms, breaking the bonds of valence electrons and pumping them up to higher energy in the conduction band as shown in Fig. 2. There, a specially made selective contact collects conduction-band electrons and drives these freed electrons to the external circuit. The electrons lose their energy by doing work in the external circuit. They are restored to the solar cell by the return loop of the circuit via a second selective contact, which returns them to the valence band with the same energy that they started with. The movement of these electrons in the external circuit and contacts is called the electric current. Electrons are pumped by photons from the valence band to the conduction band, where they are extracted by a contact selective to the conduction band (an n-doped semiconductor) at a higher (free) energy and delivered to the outside world via wires, they do some useful work, then are returned to the valence band at a lower (free) energy by a contact selective to the valence band (a p-type semiconductor).

Solar cells are interconnected and hermetically sealed to constitute a PV module. The PV modules are integrated with other components such as storage batteries to constitute SPV systems

Table 1
Advantages and disadvantages of PVs.

Advantages of PVs	Disadvantages of PVs
Fuel source is vast, widely accessible and essentially infinite	Fuel source is diffuse (sunlight is a relatively low-density energy)
No emissions, combustion or radioactive waste (does not contribute perceptibly to global climate change or air/water pollution)	Solar cells do not generate electricity at night, and in places with frequent and extensive cloud cover, generation fluctuates unpredictably during the day
No moving parts (no wear); theoretically everlasting	PV cells use rare elements that might be subject to increases in cost and restriction in supply
Low operating costs (no fuel)	High installation costs
Ambient temperature operation (no high-temperature corrosion or safety issues). High reliability of solar modules (manufacturers' guarantees over 30 years)	Lack of economical efficient energy and storage
Modular (small or large increments)	
Can be integrated into new or existing building structures	
Can be very rapidly installed at nearly any point-of-use	

and power plants. PV systems and power plants are highly reliable and modular in nature.

PV cells have been in use in spacecraft since the 1950s [12]. However, with the energy crisis of the early 1970s, a steadily growing terrestrial industry has developed. Initially, it supplied PV cells mainly for remote area applications where conventional electricity is expensive. Nonetheless, the industry is now in an explosive period of growth where the subsidized urban-residential use of PVs is providing the main market.

The advantages and disadvantages of PVs are described in Table 1. The beauty of the PV system is that it does not involve any moving parts or emissions of any kind during operation. The main attractiveness of the PV technology is low maintenance, and no pollution, and has positioned PV to be the preferred power technology for many remote applications for both space and on the ground. PV technology is expected to be a leading technology to solve the issues concerning the energy and the global environment due to several advantages of the PV system [13]. Although, silicon material is most commonly used for generation of electricity, it also has associated drawbacks, such as high material costs for silicon, costly processes for purifying silicon and manufacturing wafer, additional processes for assembly of modules and the bulky and rigid nature of the PV panels [14]. Solar energy has low energy density and PV modules require a large surface area for small amounts of energy generation [15]. The primary component in grid connected PV systems is the inverter, it convert DC power produced by PV array into AC power consistent with the voltage and power quality requirement of the utility gird. The PV system is promising source of electricity generation for energy resource saving and CO_2 emission reduction, even if current technologies are applied [16,17]. Further the development in efficiency of solar cells, amount of material used in the solar cell

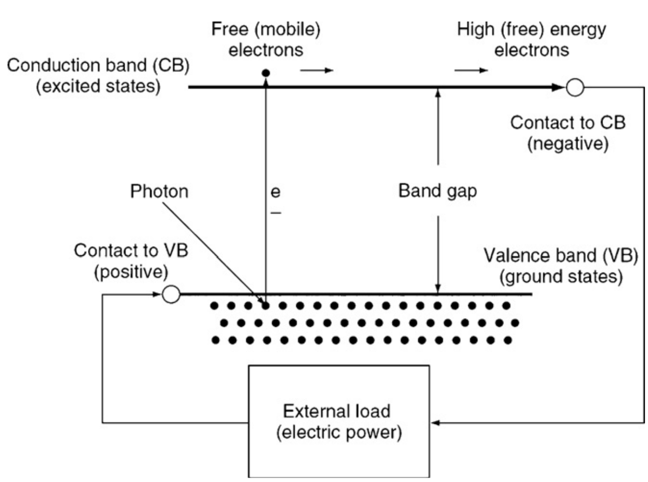


Fig. 2. Schematic of a solar cell.

and the system design for maximum use of recycled material will reduce the energy requirement and greenhouse gas emissions [18].

The present PV market is growing at the very high rate of 35–40% per year, and world PV production was 10.66 GW in 2009 [19,20]. This became possible owing to technology cost reduction and market development, reflecting the increasing awareness of the versatility, reliability, and economy of PV electric supply systems. Major market segments served by this industry comprise consumer applications, remote industrial systems, developing countries, and grid-connected systems. Of particular interest is the strong differential growth rate in rural applications, which now accounts for nearly half of the total PV market. The second largest market is industrial applications [19]. At the present, over 80% of the world PV industry is based on c-Si (crystalline Si, or c-Si, solar cells with efficiency of 6–10%) and pc-Si (polycrystalline Si) wafer technologies. The cadmium telluride (CdTe) technology is growing sufficiently fast, while thin-film copper–indium–gallium–selenide (CIGS), and a-Si-based PV production is still in the beginning stages, despite the remarkable results of R&D many years ago. Most of the leading technologies, the efficiency is already adequate, and emphasis should be on developing cost effective manufacturing technologies that can significantly lower the module production cost [19].

2.2. Concentrated solar thermal systems

Solar cells are not the only technology by which sunlight can be turned into electricity. Concentrated solar thermal systems use mirrors to focus the Sun's heat, typically heating up a working fluid that in turn drives a turbine. Fig. 3 shows the principle of (a) parabolic trough, (b) power tower, (c) parabolic dish systems, and (d) linear Fresnel reflector. The heated heat transfer fluid (e.g. pressurized steam, synthetic oil, and molten-salt) flows from the collector to a heat engine where a portion of the heat (up to 30%) is converted to electricity [21]. CSP plants consist of two parts: one that collects solar energy and converts it to heat, and another that converts the heat energy to electricity. The mirrors can be set in troughs, in parabolas that track the Sun, or in arrays that focus the heat on a central tower. All CSP technological approaches require large areas for solar radiation collection when used to produce electricity at commercial scale. CSP technology utilizes four alternative technological approaches: parabolic trough, power tower, dish/engine and linear Fresnel reflectors. The solar flux concentration ratios typically obtained are 30–100, 500–1000, and 1000–10,000 suns for trough, tower, and dish systems, respectively [22].

At present, there is rapid development occurring both in the basic technology [25] and the market strategy and prospects for rapid growth of solar thermal power [26–29]. The attractiveness of the concentrating solar power (CSP) technology over the standard PV technology is that it uses less semiconducting material by replacing most of the PV cell area with a set of

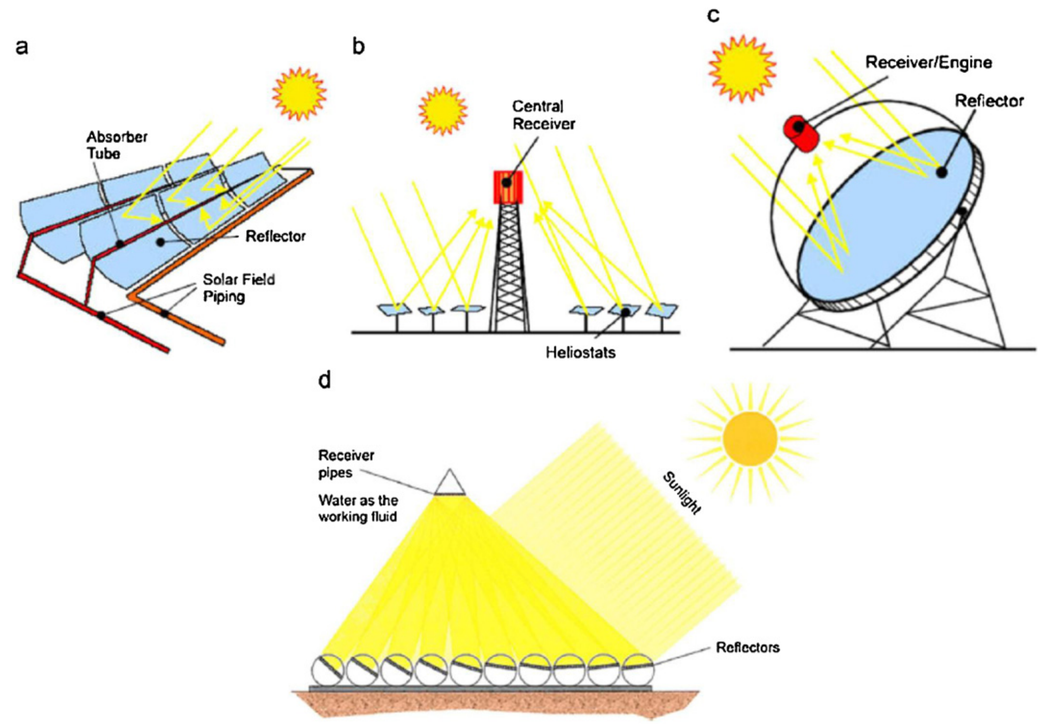


Fig. 3. Principle of (a) parabolic trough, (b) power tower, (c) parabolic dish systems, and (d) linear Fresnel reflector [23,24].

reflectors in order to reduce the cost. Additionally, increasing the concentration ratio will improve the performance of general PV materials. Concentrating PV technology offers the following advantages:

- Potential for solar cell efficiencies greater than 40%.
- No moving parts.
- No intervening heat transfer surface.
- Near-ambient temperature operation.
- No thermal mass and a fast response.
- Reduction in the cost of cells relative to optics.
- Scalability to a range of sizes.

Despite the advantages of CPV technologies, their application has been limited by the complexity and due to the cost of focusing, tracking and cooling equipment, As yet, the installed capacity is quite small, and the technology will always remain limited to places where there are a lot of cloud-free days – it needs direct sun, whereas PVs can make do with more diffuse light. Some concentrated solar thermal systems get around this by storing up heat during the day for use at night (molten salt is one possible storage medium), which is one of the reasons they might be preferred over PVs for large installations. [1,30] carried out the techno-economic evaluation of concentrating solar power generation in Indian conditions and noted that the locations blessed with annual direct solar radiation more than 1800 kWh/m^2 are best recommended for installation of CSP systems.

3. Solar energy in Pakistan

In view of the scarce fossil fuel reserves in the country, energy security and climate change concerns it is expected that renewable energy will play a significant role in Pakistan's future energy mix. Fig. 4 provides an overview of the different renewable energy sources. Renewable energy can be used for the entire spectrum of end-uses as given in Fig. 5.

Pakistan covers 796,095 km^2 of land between latitudes 24° and 36° north and longitudes 61° and 76° east. Country is facing serious energy problems. Every day, the country receives an average of about 19 MJ/m^2 of solar energy [32]. This source can be utilized

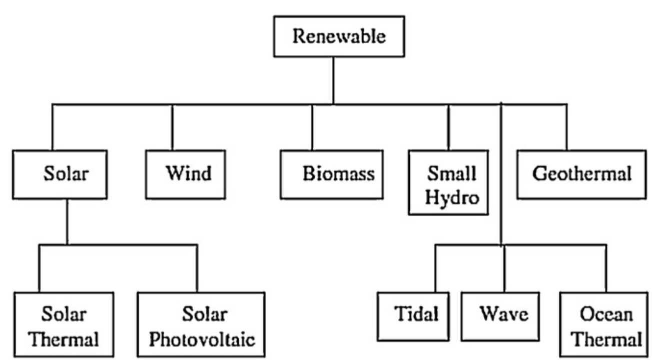


Fig. 4. Schematic of renewable energy options [31].

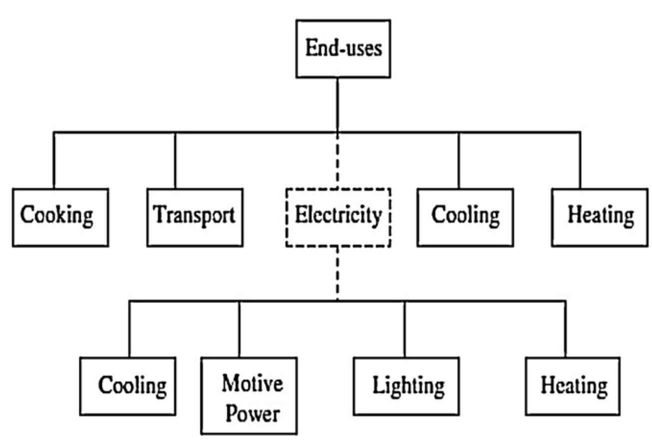


Fig. 5. Energy end-users [31].

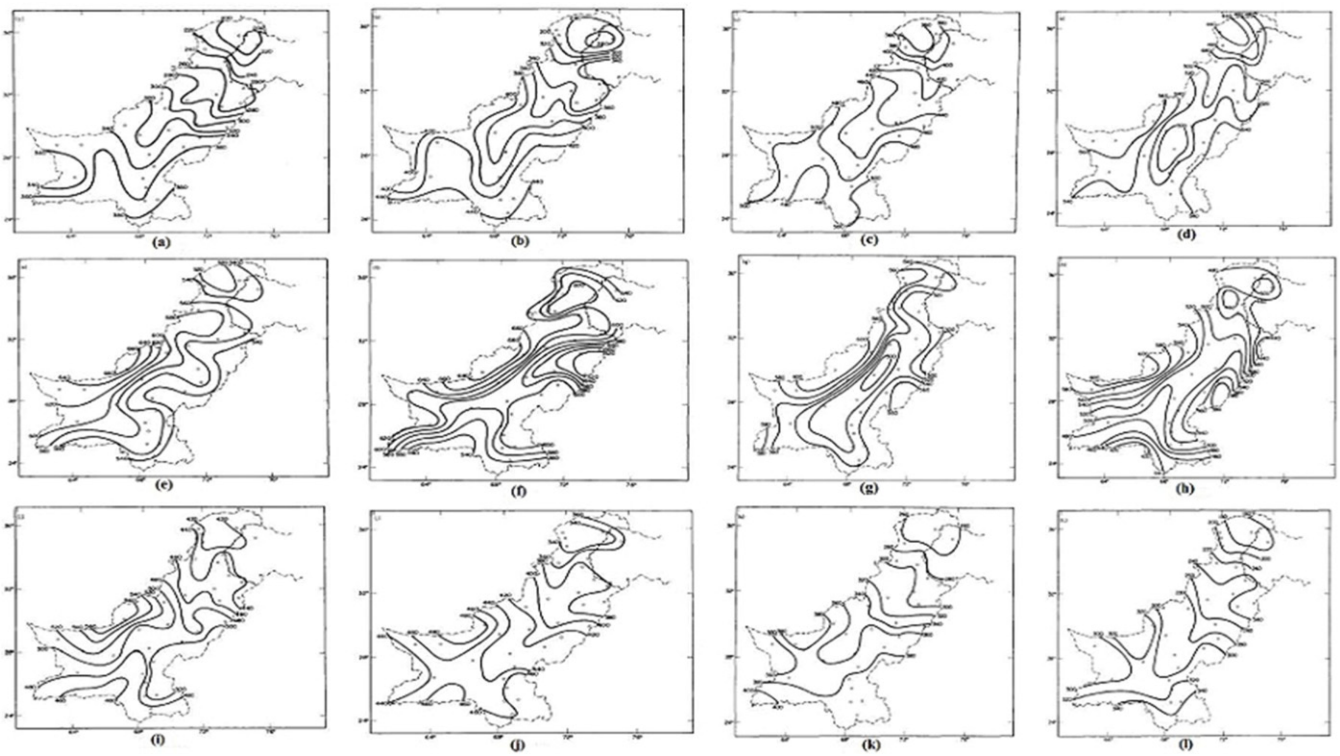


Fig. 6. Mean daily solar radiation in Pakistan (cal/cm^2/day) during: (a) January, (b) February, (c) March, (d) April, (e) May, (f) June, (g) July, (h) August, (i) September, (j) October, (k) November and (l) December [33].

as an excellent alternative to fossil fuels especially in remote areas where access to fossil fuel is very difficult and there is no access to electricity.

4. Global insolation data for Pakistan

Adequate information regarding the availability of global solar radiation and its components at a particular location is essential to predict the efficiency and performance of many solar thermal devices. For proper utilization of PV technology for energy generation, thorough and accurate knowledge of global solar radiation variation is required. In Pakistan only five stations: Karachi, Lahore, Quetta, Multan and Peshawar record global solar radiation on a horizontal surface. Therefore for other locations in Pakistan, one has to depend on the different empirical relationships which have been suggested so far for estimation purposes, employing different climatological parameters. Chaudhary [33] using Angstrom's linear relationship developed monthly and annual mean daily values of solar radiation for sunshine hours which are shown in Fig. 6. Fig. 7 represents the annual mean daily solar radiation in Pakistan. The maximum amount of solar radiation in the country is received in and around Quetta. Sind and Blochistan provinces are receiving more than 440 cal/cm^2 day, Punjab and Khyber Pakhtunkhwa (KPK) province is receiving between 400 and 440 cal/cm^2 day and the northern areas and Kashmir are receiving less than 400 cal/cm^2 day [33]. This energy source is widely distributed and abundantly available in the country. A daily average of global irradiation falling on horizontal surface is about 200–250 W/m^2. This amounts to about 6840–8280 MJ/m^2 in a year.

U.S. National Renewable Energy Laboratory (NREL) has developed high-resolution (10-km) annual and seasonal wind and solar resource maps and data resource maps of Pakistan (Figs. 8 and 9). The high-resolution (10-km) annual and seasonal solar resource maps were developed using weather satellite data incorporated into a site-time specific solar mapping approach developed at the U.S. State University of New York at Albany. Data products from solar maps have been output in a Geographic Information Systems (GIS) format and incorporated into the Geospatial Toolkit (GsT). Working within the GsT, the user can also incorporate location-specific data directly into the micropower optimization model, HOMER, to design least-cost hybrid renewable power systems to meet electric-load requirements at the village level [34].

5. Prospects of solar energy utilization in Pakistan

The prospects of solar energy utilization in Pakistan have also been extensively studied by the researchers. Sukhera [35] proposed solar energy conversion processes suiting the local conditions of the

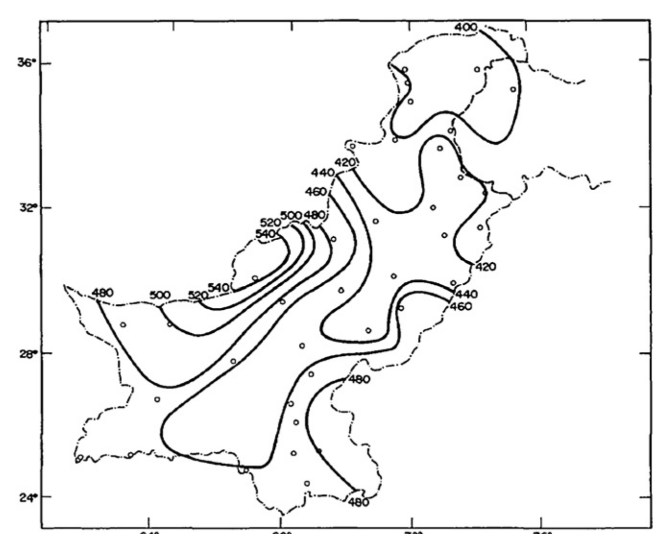


Fig. 7. Annual mean daily solar radiation in Pakistan (cal/cm^2 day) [33].

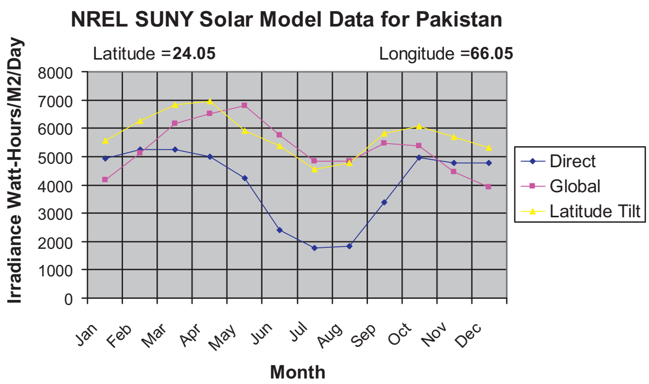


Fig. 8. NREL sunny solar model data for Pakistan [34].

Cholistan desert area. Hasanain and Gibbs [36] discussed the significance of renewable resources for the development of remote areas in Pakistan. Mukhtar [37] analyzed the economic feasibility of solar air conditioning, Lutfi and Vezirogla [38] proposed and analyzed a solar-hydrogen system for Pakistan. Iftikhar et al. [39] described the achievements of the institutional level Research and Development efforts of Pakistan, in the fields of solar thermal and PV system up to 1996 and a later outlook was presented by Mirza et al. [40] concluding that the existing infrastructure remained unable to advance the status of solar energy in Pakistan. However a comparative picture of the countries in the region painted by Roy [41] gives an encouraging outlook for Pakistan. More recently Sahira and Qureshi [42] discussed that the present status of solar energy technologies and they were of the opinion that lack of policy instruments to integrate the techno-economic and socio-political behaviors and actions, and inconsistencies of the government policies present the major barriers to the significant utilization of the solar energy. Mirza, et al. [43] suggested for adopting least cost planning in resource acquisition to ensure proper evaluation of available renewable energy options. They also suggested for indigenization of renewable energy technologies to reduce the investment costs significantly. According to Shinwar et al. [44] the cost of electricity from solar PV technology can come down by initiative from government such as indigenization of the technology and giving duty relief on import of technology. Local generation of PV cells on a commercial scale can bring about a substantial decrease in the capital prices involved in PV cells production, further decreasing the levelized cost of energy. According to Khan and Latif [45] the main constraints to widespread utilization of solar PV technologies are:

- high initial cost of PV system,
- inadequate renewable energy policy,
- unawareness in local communities,
- inadequate availability of technical know how.

Attempts have been made in Pakistan both at installing small-scale PV power generators and at creating an indigenous PV fabrication capability. The indigenous fabrication facility exists only at PCRET whose capabilities remain at pilot scale. Water and Power Development Authority (WAPDA) ventured into installing imported PV panels for small-scale power generation, but failed to sustain it. Imported solar modules are available in the open market in Pakistan, but at exorbitant prices. Clearly then, the PV solar energy technology in Pakistan could neither be sustained at the user level, nor has it been attractive to prospective investors. It would therefore be interesting to find ways that could make solar energy technology marketable in the country. Among the host of factors that form an answer to this question, one is the economic viability [44]

6. Potential applications of solar energy in Pakistan

The best way to utilize solar energy is through PVs, which convert the sun energy directly into electricity – undoubtedly the most convenient form of energy. PV technology is particularly suitable for small power requirements and remote area applications. In the early 1980s, 18 PV stations were set up by the government in different parts of the country for village electrification, with an installed capacity of nearly 440 kW. However, because of lack of technical know-how and follow up, these systems have not performed as required [40,46]. Currently PV technology is being used in Pakistan for stand-alone rural telephone exchanges,

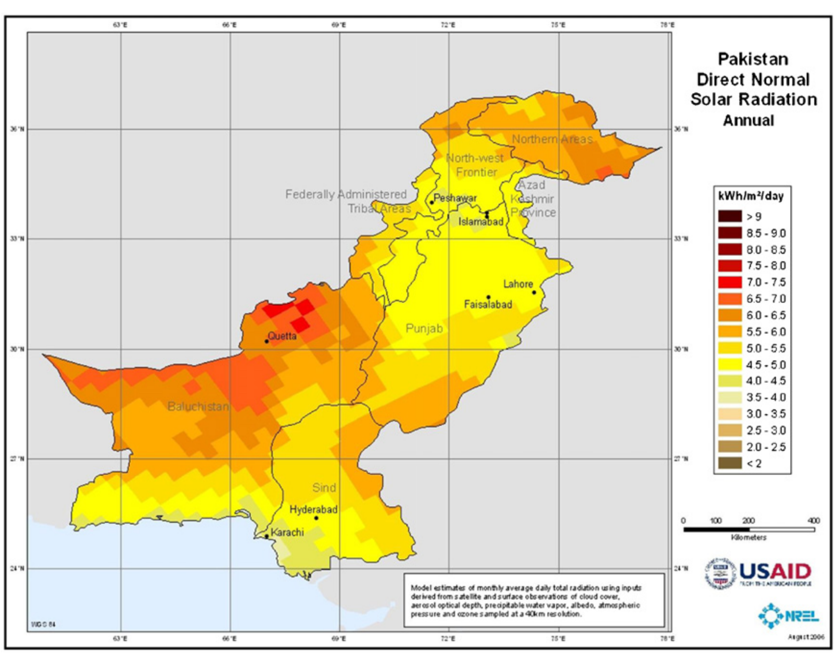


Fig. 9. Pakistan direct normal solar radiation map of Pakistan developed by NREL [34].

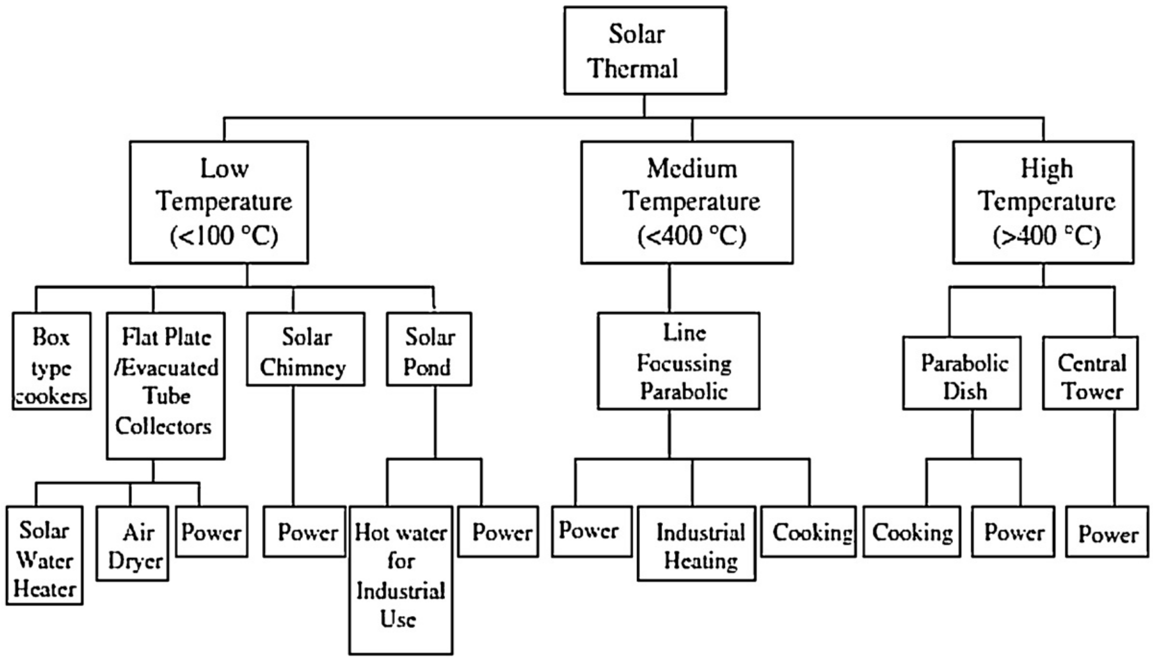


Fig. 10. End-uses and technologies for use of solar energy [31].

repeater stations, highway emergency telephones, cathodic protection, refrigeration systems for vaccine and medicines in hospitals, etc. Some initiatives are taken for use of solar energy street lamp, solar energy lawn lamp, solar energy traffic signal lamp and solar energy sight lighting. Siemens Pakistan is also actively involved in Photovoltaic business for more than 10 years. They have installed complete solar systems in all parts of the country, mainly for house electrification, telecommunication (microwave links, optical fiber and digital exchanges), water pumping, navigation, highway communication, oil and gas fields and street lighting further details are available at their website [47].

6.1. Photovoltaics

Blochistan, the largest province of Pakistan area-wise, has a population density of just 21 persons/km^2, with 77% of population living in rural areas. About 90% of the villages are yet to be electrified. These villages are separated by large distances with absolutely no approach roads. The houses are mostly 'kacha' hut type with walls and roofs made with a combination of mud and straw. Light is the only requirement for these houses. Most of the houses consist of only one room. The electric requirement for each house varies from 50 to maximum 100 W [46]. Transmission lines are very expensive to build in these areas and there is only a remote possibility of grid connection in the near future. Also, the extension of grid lines for such small power requirements is very costly. For such communities local power generation is the only possible solution to these problems. While considering diesel generators, transportation of fuel to such remote areas and maintenance are again a costly proposition. Solar PV can be a very useful technology to deliver electricity in remote applications where grid connectivity is impractical. For example, in far-off villages of Balochistan, Cholistan and Thar deserts, solar PV can be a more convenient and value engineered solution to provide electricity for basic needs [40,46]. Solar PV technology has been proven to be a viable option because of its modular size, small weight, and ease of installation. Also, adverse physical characteristics of rural areas do not hinder much the dissemination of solar PV systems [48]. The need of electricity is not only for rural areas, but the grid connected locations are also seeking the alternate electricity supplies because of big load shedding problem which last for 4–6 h in urban areas and 8–12 h in rural areas.

6.2. Solar thermal

There are a large number of applications in which solar energy can be utilized directly by exploiting its heat characteristics. Fig. 10 shows the classification of solar thermal systems based on the working fluid temperatures achieved and the end-uses.

Solar thermal technologies are comparatively simple, relatively low cost and easy to adopt. The potential applications solar thermal technologies in Pakistan includes cooking, heating and cooling of buildings, generation of high temperature steam, heating water for domestic and industrial applications, and drying agricultural products under controlled temperatures. A brief description of these applications in Pakistan is provided here.

6.2.1. Solar desalination

One of the major problems in Cholistan and Thar deserts is the scarcity of fresh water. Peoples are forced to consume brackish to saline groundwater. Except for a few places, the subsoil water is brackish and is not fit for human or animal consumption [35]. Further, along the coastline in Balochistan, seawater is abundant but potable water is not available. Solar desalination has wide application for the populations living in rural areas of southern Punjab and Sindh and coastal areas of Balochistan [49].

Solar energy desalination is a method by which the sun's energy is used to desalinate brackish or seawater to produce fresh drinkable water. There are two methods for using solar energy: directly by heating and evaporating the brackish or seawater in a solar still (this method is called solar distillation) and indirectly by capturing solar energy using one of the techniques that transform solar radiation into thermal or electrical energy to drive a conventional desalination method (the indirect method is called solar-assisted or solar driven desalination) [50].

Arjunan et al. [51] has discussed the types and working of solar distillation plant. They have also provided the lay out of solar distillation plant installed at Village Awania, India and analysis of design

aspects in detail. Authors concluded that solar distillation is the best solution for remote areas and small communities in arid and semi-arid regions with lack of water.

The simplest form of water still in use basically consists of a shallow tray filled with salt or brackish water and covered by a sloping glass cover plate. The solar radiation heats the water in the tray and evaporates it. When the vapor comes in contact with the colder surface of the glass, it condenses, forming fresh water which runs down the inner surface in the form of droplets and can be collected in a trough at the lower edge. Under good radiation conditions an output of about 4 kg/m^2 of fresh water can be obtained daily.

Two plants consisting of 240 stills each with a capacity to clean 6000 gallons of seawater per day have been installed in Gawadar in Balochistan. A number of such schemes are under active consideration by local governments in Balochistan and Thar Desert region of Punjab and Sindh [49]. The solar desalination technology is simple, low cost and low-tech, and therefore, it can easily be adopted by local rural people [49]. An optimized glass cover single basin solar still fabricated by Pakistan Institute of Engineering and Applied Sciences (PIEAS) was calculated as 30.56% efficient which is comparable with stills being used worldwide. The cost effective design is expected to provide the rural communities an efficient way to convert the brackish water into potable water [49,52] has recently illustrated six alternate for low temperature, low-pressure desalination systems that has the potential to be driven by low grade heat sources such as waste heat and/or solar energy. The cost effective design of desalination solar is expected to provide the rural communities an efficient way to convert the brackish water into potable water.

6.2.2. Solar water pump

The Cholistan desert in Pakistan is characterized by low and sporadic annual rainfalls, low values of relative humidity, high rate of evaporation, high degrees of solar radiation and strong summer winds. The only source of water supply for human and livestock in part of Sindh and large parts of Punjab Province is rainwater accumulated in low-lying areas which get dry mainly through evaporation during hot summer. The people living there have to face many problems including the scarcity of water and vegetation with the result that they follow a nomadic way of life, moving about with their flocks and herds and continually seeking pastures. Quality of life of these people is very poor and they make little contribution to the national growth. It is of utmost importance for our national growth, balanced regional development and attainment of a reasonably good standard of living for the people that we should develop the arid zones and make them as productive as possible. Underground water can also be lifted by using PVs and direct conversion of solar energy into electrical energy. At certain places where the subsoil water is potable, irrigation is carded on in a very slow and ineffective way by using bullock power. To pump water from wells, an inexpensive engine of 1 or 2 hp could be quite effective. Pakistan Atomic Energy Commission designed a solar water pump which utilizes a 21 ft diameter paraboloid fitted with flat mirrors, boiler and a steam engine. It provides 2 hp to the pump [35]. Imported PV pumps have also been tried in Pakistan by farmers. These pumps were given to them by the Agricultural Development Bank of Pakistan (ADBP) for field trials in different parts of the country. The main bottleneck in the introduction of these pumps for irrigational purposes is their high initial investment. In China, the irrigation object area of solar water pump in 2010 is more than 392,000 ha, and the need of PV for solar water pump is more than 261 MW [53]. Pakistan can take benefit from the Chinese experience in solar water pumping to improve pumping groundwater for both drinking purpose and for irrigation in Balochistan Province.

6.2.3. Solar water heaters

Solar water heating, one of the oldest and the most successful applications of solar thermal technologies, utilizes solar energy to heat water without producing harmful emissions into environment. It is also one of the fastest growing renewable technologies in the world [54]. According to Asif [54], solar water heating, one of the fastest growing renewable technologies in the world exhibits a healthy potential in Pakistan with a reported pay back period of less than 3 years.

Solar water heating technology is quite mature but its use in Pakistan has been quite limited so far mainly because of higher capital cost of solar water heater as compared with conventional ones operating on natural gas. A number of public sector organizations are actively working on the development of low cost solar water heaters that have now started gaining popularity particularly in the northern mountainous regions due to cold weather and limited and difficult supply of natural gas in these areas. With the electricity and natural gas prices registering sharp increases, the use of solar water heaters is bound to increase. The production and commercialization of such heaters has already been started in the private sector [55]. Alternative Energy Development Board (AEDB) recently launched a Consumer Confidence Building Program for the promotion of Solar Water Heaters in the country. The program was designed to create awareness of solar water heating technology and to build the consumer confidence on the product through a number of incentives to buyers that includes money back guarantee. AEDB is also working for the deployment of 20,000 solar water hearers in Gilgit Baltistan [56].

Evaluation by Han et al. [57] reveals that using solar water heaters instead of conventional (gas and electric) water heaters has great economic benefits (saving fuel costs), environmental benefits (reducing fossil fuel consumption and pollutants emission) and social benefits (cheaper, cleaner and safer hot water for daily life).

6.3. Solar water heating in industry

Solar water heating, besides its domestic role, has a wide array of applications within commercial (such as swimming pools, laundries, hotels and restaurants) and industrial sectors (such as food and beverages, process, and textile industries). While in the industrial sector, water heating may account for a significantly higher share of energy. In the textile sector water heating can account for as much as 65% of the total energy used during process such as dyeing, finishing, drying and curing [58]. Solar thermal systems are particularly effective in industries that require water temperatures in the range 40–80 °C [59]. The most important industrial processes using heat at a mean temperature level are: sterilizing, pasteurizing, drying, hydrolyzing, distillation and evaporation, washing and cleaning, and polymerization. Some of the most important processes and the range of the temperatures required for each are outlined in Table 2. Table 3 gives a rough overview over the processes suited for solar heat and the industrial sectors where they might typically occur.

In a solar process heat system, interfacing of the collectors with conventional energy supplies must be done in a way compatible with the process. Fig. 11 shows the possibility of combining the solar system with the existing heat supply.

In Pakistan textile industry is a major sector in which solar energy can be practically utilized. Pakistan is the world's fourth largest producer and consumer of cotton. Pakistani textile industry is facing a tough challenge in the form of global environmental standards. The textile industry is a key sector of Pakistan's economy but also one of the most energy intensive industries. High energy prices and the widening gap between demand and supply have a negative impact on the productivity and competitiveness of the country's industry. Energy efficiency is a crucial issue in a

Table 2
Temperature ranges for different industrial processes [60].

Industry	Process	Temperature (°C)
Dairy	Pressurisation	60–80
	Sterilisation	100–120
	Drying	120–180
	Concentrates	60–80
	Boiler feed water	60–90
Tinned food	Sterilization	110–120
	Pasteurization	60–80
	Cooking	60–90
	Bleaching	60–90
Textile	Bleaching, dyeing	60–90
	Drying, degreasing	100–130
	Dyeing	70–90
	Fixing	160–180
	Pressing	80–100
Paper	Cooking, drying	60–80
	Boiler feed water	60–90
	Bleaching	130–150
Chemical	Soaps	200–260
	Synthetic rubber	150–200
	Processing heat	120–180
	Pre-heating water	60–90
Beverages	Washing, sterilization	60–80
	Pasteurization	60–70
Timber by-products	Thermo diffusion beams	80–100
	Drying	60–100
	Pre-heating water	60–90
	Preparation pulp	120–170
Bricks and blocks	Curing	60–140
Plastics	Preparation	120–140
	Distillation	140–150
	Separation	200–220
	Extension	140–160
	Drying	180–200
	Blending	120–140

global market where productivity and competitiveness are major performance indicators. Water heating system as required for dying process is one of the major energy consuming areas in fossil fuel-run Pakistani textile industry. In textile wet processing, water is used mainly for two purposes; firstly, as a solvent for processing chemicals and secondly as a washing and rinsing medium. Apart from this, some water is consumed in ion exchange, boiler, cooling water, steam drying and cleaning. The typical hot water usage within a medium-sized textile mill is 500 tons raised to 40 °C (for washing and cleaning of cotton loom), 300 tons raised to 60 °C (for cotton dyeing and production of viscose) and 200 tons raised to 80 °C (for production of synthetic, polyester material). Thus the total hot water consumption is 1000 tons/day [61]. Solar water heating is a potential candidate to replace the conventional energy sources in textile industry and can be an economical choice. Adopting this technology can also substantially reduce the environmental impacts. Muneer et al. [62] estimated the payback period for solar water heating incorporated within textile industries in Pakistan to be 6 years. In same work they have presented work proposes the introduction of built-in-storage water heaters for Pakistani textile industry due to its low cost and simple construction as compared to thermosyphon heaters. Muneer et al. [61] has discussed Prospects for solar water heating within Turkish textile industry and estimated the payback period for solar water heating incorporated within textile industries in Turkey to be 5.6 years while life cycle assessment show that the embodied energy and carbon payback period for both of the heaters is 2.3 and 0.8 years, respectively.

Table 3
Operations and processes in some important industrial sectors (x – important, X – very important).

Process industry sector	Food	Textile	Building material	Galvanizing, electroplating	Fine chemicals	Pharmaceutical and biochemical	Services	Paper	Automobile supply	Tanning	Paint	Wood and wood products
Cleaning	X	X	x	X	x	X	X		x	x	X	
Drying	X	X	x		x	X	X	x	x	X	X	X
Evaporation and distillation	X				x	X						
Pasteurisation	X					X						
Sterilization	X					X						
Cooking	X											
General process heating	x	x	x	X	x	x	X		x			x
Boiler feed water preheating	X	X	x		x	x		x		x		
Heating of production halls	X	X		x	x	x	x		X	X	X	X
Solar absorption cooling	X			x		X	X					

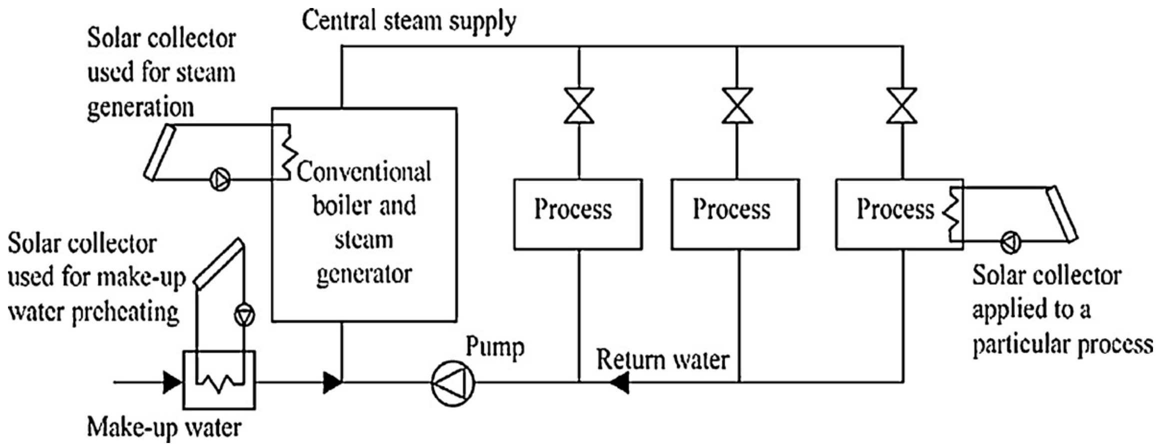


Fig. 11. Possibilities of combining the solar system with the existing heat supply [60].

6.4. Solar cooker

Among the different energy end uses, energy for cooking is one of the basic and dominant end uses in developing countries. As most items cooked have high water content, cooking requires temperatures only in the order of 90–100 °C (except for frying). Lof [63] has described the principles of cooking. As per his principle, the energy requirement is at maximum during the sensible heating period. Heat required for physical and chemical changes involved in cooking is less. The energy required for a specific cooking operation is not always well defined and can vary widely with the cooking methods used. During cooking, 20% of heat is spent in bringing food to boiling temperature, 35% of heat is spent in vaporization of water and 45% of heat is spent in convection losses from cooking utensils. Insulating the sides of the vessel and keeping the vessel covered with a lid can considerably reduce the heat losses. So, once the contents of the vessel have been sensibly heated up to the cooking temperature, the speed of the cooking is practically independent of the heat rate, as long as thermal losses are supplied. Thus, differences in the time required to cook equal quantities of food are mainly due to different sensible heating periods [64]. Higher temperatures of course, have the advantage of reducing the cooking time.

The use of solar cookers is much needed in regions with good solar radiation intensity. The reasons are economical, as the price of fuel for cooking is no longer affordable by many families; ecological, as in many regions deforestation is also associated with the use of wood as an energy source; and social, as the money used to buy fuel could be used to buy food, medications and other needs to improve the quality of life.

Solar cookers without storage are classified into direct and indirect solar cookers depending upon the heat transfer mechanism to the cooking pot. Direct type solar cookers use solar radiation directly in the cooking process while the indirect cookers use a heat transfer fluid to transfer the heat from the collector to the cooking unit. Commercially successful direct type cookers are box type and concentrating type cookers [64].

Four types of solar cookers are presented in Fig. 12 and they are defined as [65]:

(a) Flat plate collector with direct use – type A;
(b) Flat plate collector with indirect use – type B;
(c) Parabolic reflector with direct use – type C;
(d) Parabolic reflector with indirect use – type D.

In flat plate collector (type A), the cooking pot is placed directly in the collector. In the indirect system (type B), the energy is transported from the collector to the cooking place by a heat-transfer medium. In type C, a parabolic reflector concentrates the sunlight on the cooking pot. Similarly to type B, type D uses a heat-transfer medium, as shown in Fig. 12. The parabolic reflector works correctly only when it is tracks the sun rays, whereas a flat plate collector may be installed in a fixed position. Indirect systems can use large surface to collect the solar energy efficiently and they do not have any principle limitations of the size. The use of a thermal storage and integration of the cooking place in a house are possible [65].

Muthusivagami et al. [64] has carried out the review study of all the research and development work carried out in the field of storage type solar cookers. They have also discussed the classification, design and construction and working of solar cookers in details. In order to have a more complete view of solar cookers, in addition to thermal performance other friendliness and handling characteristics are necessary. These characteristics are safety of operation to avoid burning and other risks; easiness of transportation and assembly; tracking requirements and procedures; pot access and easiness of stirring; mechanical stability; robustness and life time. All these characteristics are to be considered when installing a cooker in community [64].

In Pakistan a number of public sector organizations have worked in the past and are still working on the development of low cost and efficient designs of both box and concentrator type solar cookers. Non-governmental organizations are also active in this field and have supplied a number of such cookers to camps of Afghan refugees. The Pakistan Council for Renewable Energy Technologies (PCRET), which is later described in this paper, routinely organizes training workshops on the use and maintenance of such devices [55]. The number of solar cookers in use in Hindu Kush-Himalayan (HKH) is more than 2000, but it is still far less than that being used in similar regions in China (60,000) and India (about 14,500) [40]. Pakistan needs to popularize solar cooker use in the HKH region in order to reduce the use of precious forest resources as fuel wood. Recently PCRET submitted a PC-1 to (PSDP) Public Sector Development Programme, Govt of Pakistan for dissemination of 10,000 parabolic solar cookers in remote of Sindh Province.

All Pakistani dishes including parathas and chappati can be prepared on concentrated type cooker in the same time interval as taken by a conventional single stove gas cooker. The method of cooking is also similar to that of conventional cooker. The cooker emits no harmful smoke to harm eyes and lungs of the cook. The cooking can be done on this cooker from 9:00 am to 3:00 p.m. on all sunny days of the year [66].

The main hurdle in dissemination of solar cooker are resistance to acceptance as it is a new technology, intermittent nature of sunshine, limited space availability in urban areas, higher initial costs and convenience issues. The growing urban lifestyle also warrants

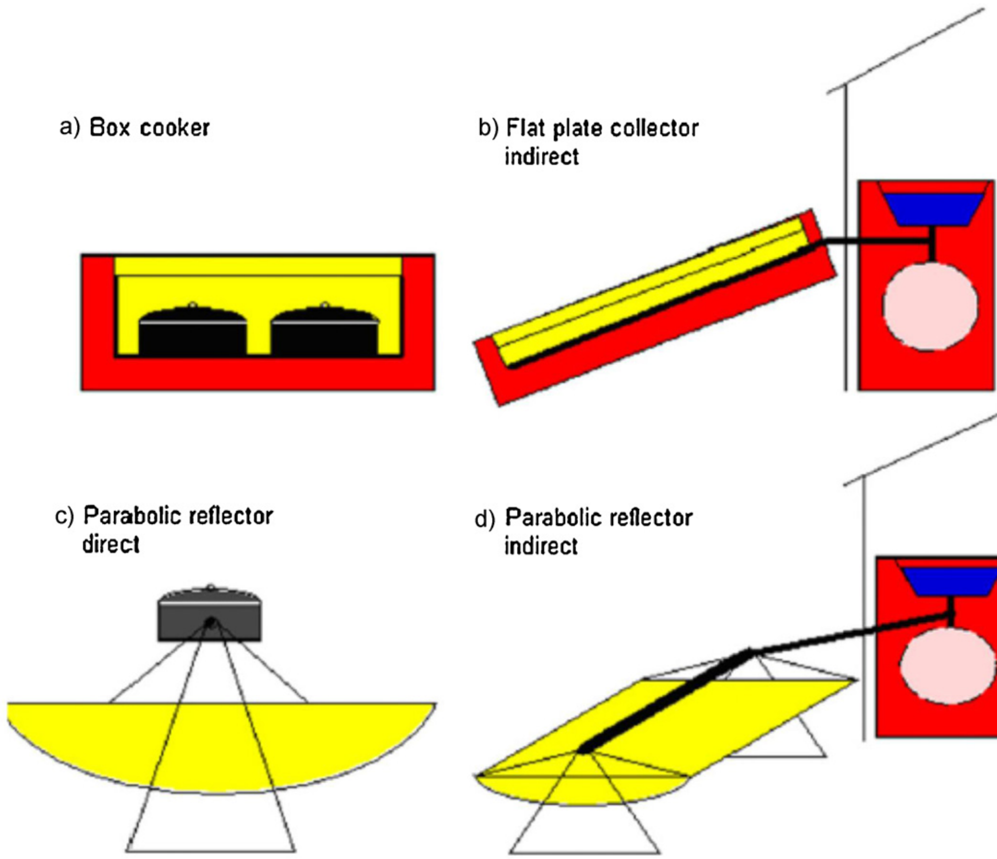


Fig. 12. (a–d) General types of solar cookers [65].

faster cooking possible in future [64]. Hence a lot of research initiatives and promotional schemes are required for the successful commercialization of solar cookers as a substitute for conventional cooking devices.

The use of solar ovens cannot completely replace conventional fuels. But to the extent that solar ovens can be used, they will greatly reduce deforestation, air pollution, and family health problems, and will conserve conventional fuels. Box type direct solar cookers are well suited to the farmers for their noon meal cooking. It is successfully commercialized in many parts of India. The large-scale utilization of this form of energy is possible only if the effective technology for its storage can be developed with acceptable capital and running costs [64]. Suitable indoor cooking unit for all time cooking similar to the conventional mode is yet to be developed, however, Muthusivagami et al. [64] has provided the designing of modular indoor kitchen for commercial and residential application is reported.

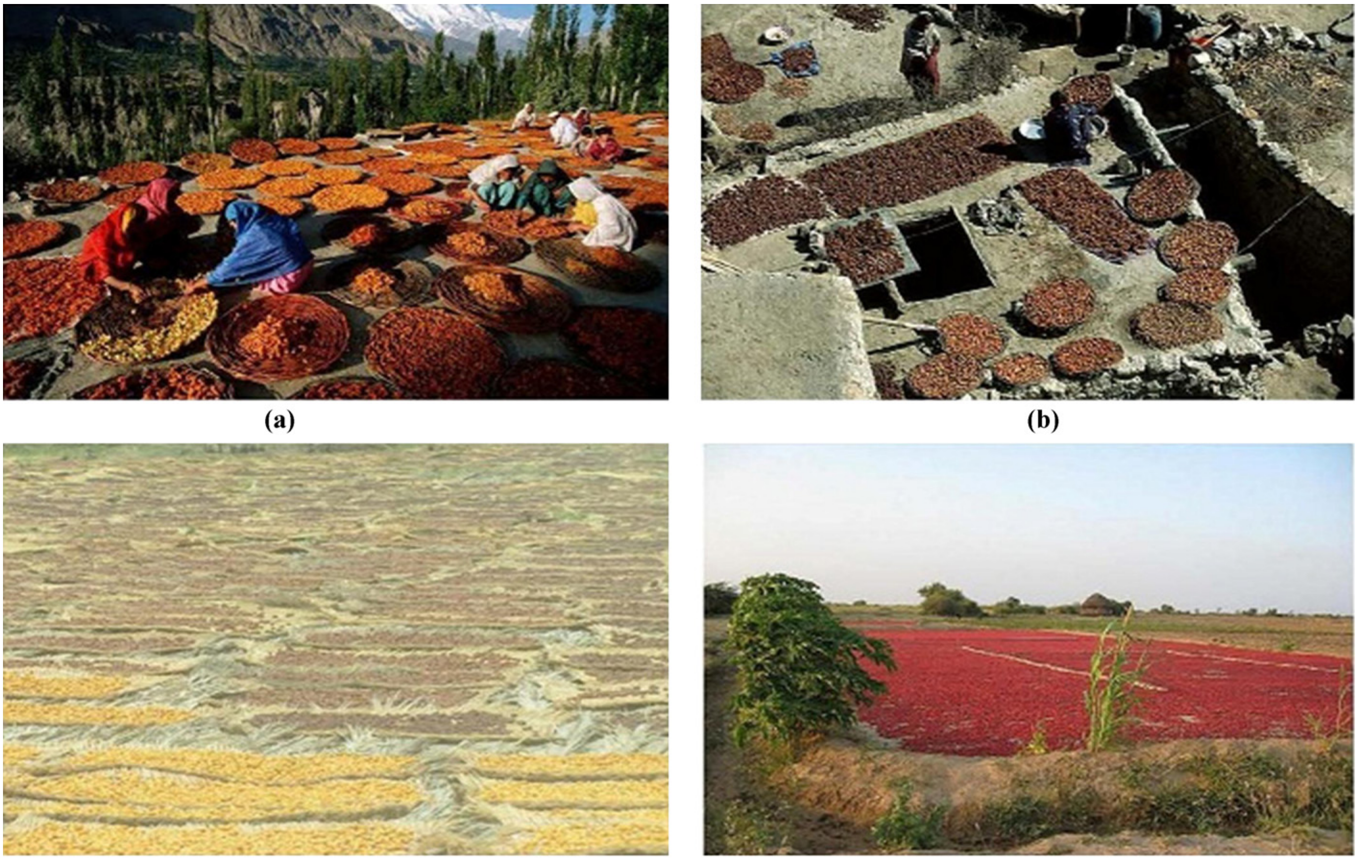
6.5. Solar dryers for agricultural products

Traditionally all the agricultural crops were dried in the sun. Drying is one of an important post handling process of agricultural produce. It can extend shelf life of the harvested products, improve quality, improve the bargaining position of the farmer to maintain relatively constant price of his products and reduces post harvest losses and lower transportation costs since most of the water are taken out from the product during the drying process. Direct sun drying requires large open space area, and very much dependent on the availability of sunshine, susceptible to contamination with foreign materials such as dusts, litters and are exposed to birds, insect and rodents. Hence, most agricultural produce that is intended to be stored must be dried first. Otherwise insects and fungi, which thrive in moist conditions, render those unusable [67]. Drying by solar radiation can be divided into two main categories:

(a) Direct, or open-air sun drying, the direct exposure to the sun.
(b) Indirect solar drying or convective solar drying.

Food materials and crops are very sensitive to the drying conditions, therefore drying must be performed in a way that does not affect seriously their color, flavor, texture or nutritional value. Thus the selection of drying conditions, as temperature, is of major importance. Many products need pretreatment, similar to pretreatment applied to conventional drying systems. For solar drying some products are pretreated to facilitate drying or to keep their flavor and texture. Outdoor sun-air heating suits to fruits. Their high sugar and acid content makes the direct sun drying safe. In the contrary vegetables have low sugar and acid content increasing the risk of spoilage during sun- and open-air drying [68].

Various solar dryers have been developed in the past for the efficient utilization of solar energy. Fudholi et al. [67] reviewed of these types of solar dryers with aspect to the product being dried, technical and economical aspects. The technical directions in the development of solar-assisted drying systems for agricultural produce are compact collector design, high efficiency, integrated storage, and long-life drying system. Fudholi et al. [67] also given the systematic classification of available solar dryers for agricultural products, based on the design of system components and mode of utilization of solar energy. Belessiotis and Delyannis [68] have also described various direct and indirect solar drying applications and some of the numerous solar dryers. A very short historical description of solar drying through the centuries is also given. Some drying phenomena, independently of the type of energy used, and the general laws that govern drying methods by convection are



(a) (b) (c) (d)

Fig. 13. Natural solar drying of fruits and agricultural product in Pakistan: (a) Pakistan – Hunza women sort freshly picked apricots and arrange them on circular mats for sun drying. (b) A villager dries freshly harvested fruits and grains on the rooftop in Altit, Gojal, Pakistan. (c) Dates drying in Sukkur, Pakistan. (d) Round chillies drying in the sun in Nagarparkar, Sindh, Pakistan.

shortly analyzed in order to easily understand the details of the solar drying procedure. According to Belessiotis and Delyannis [68], the main reasons for selecting solar energy for drying may be two:

- Energy saving. This is achieved in the cases where in the drying system, energy fraction is higher than auxiliary energy.
- The lack of availability of conventional energy sources to remote and rural areas, or the high cost of transportation of fuel to those areas.

Many studied have been reported on solar drying of agricultural products [69,70]. Numerous types of solar dryers have been designed and developed in various parts of the world, yielding varying degrees of technical performance. Basically, there are four types of solar dryers, direct solar dryers, indirect solar dryers, mixed-mode dryers and hybrid solar dryers [71].

The energy requirement for agricultural products can be determined from the initial and final moisture content of each product. Products have different drying rate and maximum allowable temperatures are given in work of [67]. The larger portion of energy consumed during drying is for transforming liquid water into its vapor (2258 kJ/kg at 101.3 kPa). Water may be contained in various forms, e.g. as free water, bound water, etc. which is related directly to the drying rate. Free or loose held water is regarded as unbound and the product is non hygroscopic. Bound moisture is trapped in closed capillaries and the material is called then hygroscopic. A very important quantity is the drying rate, determined by the temperature and moisture content of the product as well as the temperature, relative humidity and velocity of the drying air. Agricultural products are hygroscopic and thus drying rate is of main importance.

In many countries the use of solar thermal systems in the agricultural area to conserve vegetables, fruits, coffee and other crops has shown to be practical, economical and the responsible approach environmentally [72]. Solar heating systems to dry food and other crops can improve the quality of the product, while reducing wasted produce and traditional fuels – thus improving the quality of life. Solar food dryers are available in a range of size and design and are used for drying various food products. It is found that various types of driers are available to suit the needs of farmers. Therefore, selection of dryers for a particular application is largely a decision based on what is available and the types of dryers currently used widely [72]. Solar dryer technology can be used in small-scale food processing industries to produce hygienic, good quality food products. At the same time, this can be used to promote renewable energy sources as an income-generating option.

In Pakistan overproduction of fruits and vegetables lead to waste, depressed prices and lower returns to farmers. Substantial quantity of country's grain and fruit production is wasted because of inadequate and improper storage facilities. Open air natural solar drying the most common method of drying agro-commodities (Fig. 13) which result in large spoilage and quality deterioration. Traditional sun drying methods often yield poor quality, since the product is not protected against dust, rain and wind, or even against insects, birds, rodents and domestic animals while drying. Soiling contamination with microorganism, of mycotoxins, and infection with disease-causing germs are the result. Use of solar energy for drying in industries can also offer advantages like better quality of

Table 4
National actors on renewable energy: public sector.

Institution	Location	Institution	Location
1. Pakistan Council of Renewable Energy Technologies (PCRET)	25, H-9, Islamabad	2. Ghulam Ishaq Khan Institute of Science and Technology (GIKI)	House No. 77, St. 45, F-10/4, Islamabad
3. National Energy Conservation Center (ENERCON)	G-5/2, ENERCON Building, Islamabad	4. Planning & Development Division	Chughtai Plaza, Blue Area, Islamabad
5. Alternative Energy Development Board	Islamabad	6. Agriculture Technology	ADBP Head Office, Islamabad
7. PCSIR Laboratories Complex	16, H-9, Islamabad	8. Department of Physics University of Karachi	Karachi
9. COMSATS	G-5/2, Constitution Avenue, Islamabad	10. Institute of Plant and Environmental Protection (IPEP)	Islamabad
11. Pakistan Institute of Engineering and Applied Sciences (PIEAS)	Nilore, Rawalpindi	12. Hydrocarbon Development Institute of Pakistan	230, Nazimuddin Road, F-7/4, Islamabad
13. COMSTECH	G-5/2, Constitution Avenue, Islamabad	14. Mechanical Engineering Department, NED University of Engineering & Technology	Karachi

the product, less pollution and freedom from unreliable supply of fossil fuel or electricity. Solar energy can be utilized very effectively in drying agriculture products using solar dryers, and good quality products can be obtained at much less cost due to savings in cost of electricity or other heating fuels that would have been used otherwise for the same purpose. Due to the lack of logistics and basic infrastructure in the northern mountainous regions like Gilgit and Sakarduthousand of tons of fruit like apricots are wasted annually. Solar dryers can be employed to dry large quantities of such fruit and transport and sell them later in the urban market, resulting in a positive effect on the economy of this area. Different Non Governmental Organizations (NGOs) are actively working to popularize the use of such dryers. Solar dryers could be equally effectively used in the provinces of Punjab and Sindh to dry agriculture products for better market value and generating local employment [55].

In Pakistan Hussain et al. [73] fabricated direct and indirect naturally thermo convectional dehydrators in the combined mode using indigenous materials to assess their efficacy in drying fruits and vegetables at pilot scale. A variety of agricultural products were dried to test their practical usefulness. While testing the working of the dehydrators in this study, the parameters of monitored were collector plate temperature; inner space temperature of the drying chamber; ambient temperature; time spent in dehydration for different food items; percentage of water removed from the solid flesh of the item and quality of the end dried product obtained. Results clearly indicated that all the food items to be dried in the direct dehydrator took about 6 h whereas the indirect dehydrator took almost less than 4 h hence they found later more efficient than the former throughout the experimental period. The reason of its high efficiency lied in collection of more heat in the drying chamber and the uniform and refined air circulation control, which immediately removed moisture collected in the drying chamber [74]. The drying time of both the dehydrators and drying process could be conveniently completed within a limited time during clear and sunny day. Based on the performance and quality of dried products, Hussain et al. [73] recommended use of indirect dehydrator for domestic and commercial drying of agriculture products. This hydrator is low cost, simple in design, simple in use, easily fabricate able from the indigenous material at nominal cost.

Such dehydrators can dry fruits, vegetable, gains, peeled corn, legumes, paddy and any sort of commonly available agricultural products available at affordable costs in their peak season and needed to be used for certain processing like paddy to process into rice or off season use. These dehydrators can be conveniently used in remote and rural areas like northern areas of Pakistan where abundant fruits like apricot, pomegranate, figs, raisins are available that can be marketed to big cities at later times or in off season. Their practical importance is even greater for the villages, where there is no regular supply of fruits and vegetables throughout the year [73].

7. Solar–hydrogen hybrid electric power plants

In central and southern Pakistan (between 24°N and 32°N) generation of electricity through solar–hydrogen hybrid electric power plants directly with solar-induced updraft wind energy is highly feasible [75]. Solar–hydrogen hybrid electric power plants consist of a solar updraft tower power plant, also called “solar chimney”, that utilizes a combination of solar air collector and central updraft tube to generate a solar energy-induced convective flow, which drives pressure staged turbines to generate electricity and hydrogen. During solar-active periods, along with direct generation of electricity, hydrogen can be produced by photo electrolysis of river water and can be stored for use as a raw material for fertilizer production, petroleum-refining, and as a future transport fuel. Although initially such plants are somewhat more expensive than pollution-loaded oil/coal-fired power plants, nonetheless the costs are expected to become comparable, with low recurrent expenditures, and clean energy is the output. The technology is simple, reliable and accessible to the less industrialized countries [75].

8. Public Sector Organizations working to promote and disseminate renewable energies

In Pakistan most of the research, development, promotion and dissemination work in the field of renewable energy is carried out by Public Sector Organizations. Information about the public sector national actors on renewable energy is given in Table 4.

A number of solar thermal appliances including solar cookers, solar water heaters, solar fruit and vegetable dryers, solar desalination stills and solar space heating system have been indigenously developed and locally fabricated by PCRET and sections of Pakistan Council of Scientific and Industrial Research (PCSIR), National University of Sciences and Technology (NUST), Commission on Science and Technology for Sustainable Development in the South (COMSATS), Ghulam Ishaq Khan Institute of Science and Technology (GIKI) and different departments of Engineering Universities etc. Many NGOs are popularizing these devices in the country.

8.1. Pakistan Council of Renewable Energy Technologies (PCRET)

PCRET is research and development organization in Pakistan working in the field of Renewable Energy Technologies. PCRET has developed the know-how and processing technologies in the field of solar cells, modules and systems (Fig. 14). Its research

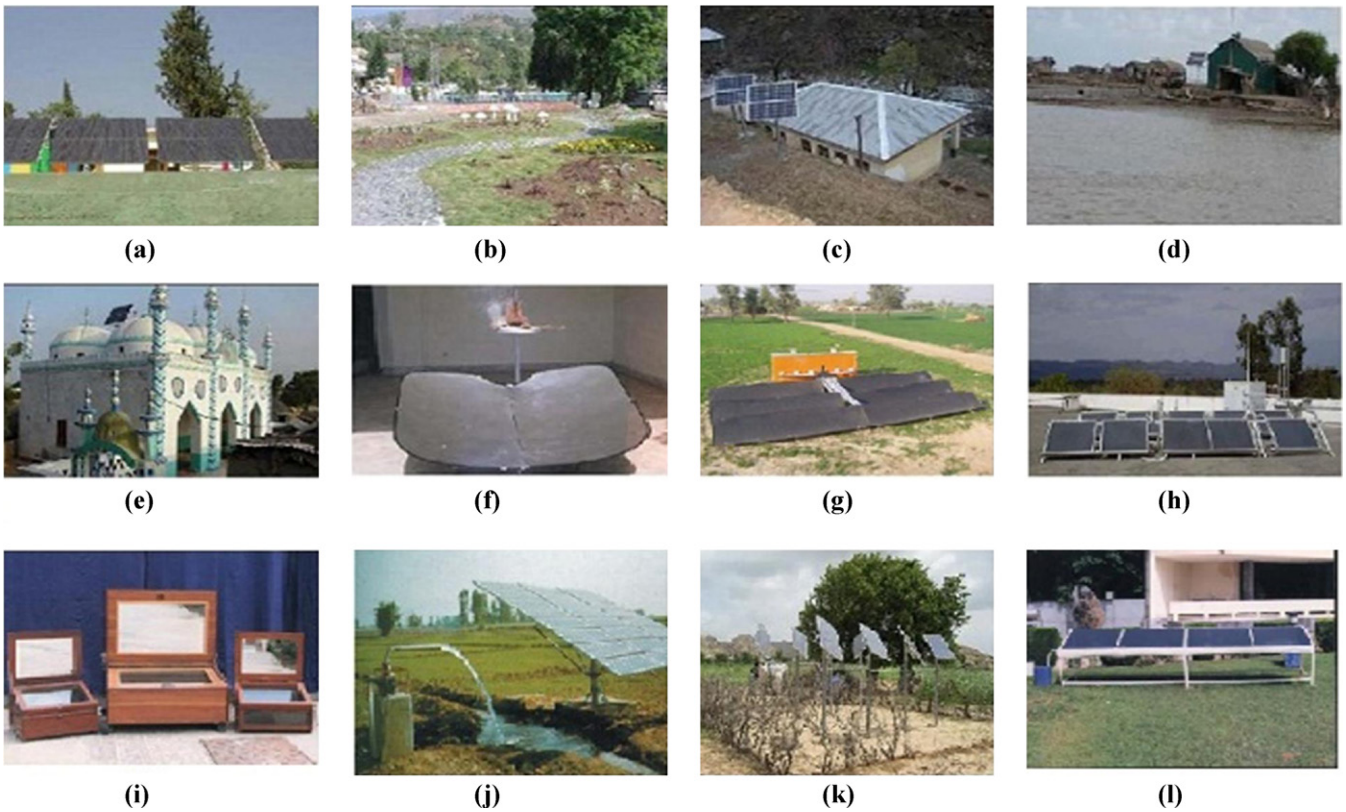


Fig. 14. Solar cells, modules and systems developed by PCRET [76]: (a) Solar powered system at Jalalabad Park Azad Kashmir, Pakistan. (b) Solar powered garden lights At Muzafarabad, Azad Kashmir Pakistan. (c) 400 W solar lighting system installed at school of remote area of Pakistan. (d) A mosque lit by 200 W solar powered system at the Kettibander Island of Pakistan. (e) 200 W solar powered system at a mosque in Thar area. (f) Parabolic type solar cooker developed by PCRET (reflecting material: aluminium foil, dish material: fibreglass and cement, stand made of angle iron). (g) Solar dryer for drying of fruits and vegetable 500 kg capacity. (h) Solar water heating system for space heating. (i) Solar box type cooker developed by PCRET (body: wooden, and iron sheet, reflecting material: ordinary glass and transparent glass, heat retaining material: glass or rock wool). (j) Solar powered tube well. (k) Solar panels being used for water extraction in Rarkou village in Nagarparkar, Sindh. (l) Desalination solar still at PCRET.

laboratories are equipped with facilities of growing silicon monocrystalline ingots, slicing the ingots into wafers, fabrication of solar cells and devices and lamination of cells into PV modules. As a result, a number of products are being fabricated on a limited scale in the Council's laboratories. These include silicon wafers, Solar cells, PV modules, PV systems, such as solar lantern/torch, home light systems, street lights/park lights, solar fountain, solar mobile charger, etc. A number of such systems have been designed and installed for applications of lighting, fencing, water pumping and telecommunication. PCRET is up-grading its laboratory facilities under a PSDP project by constructing new laboratories, equipped with new state-of-the-art facilities which will enhance its solar module production capacity up to 80 kW annually extendable to over 1 MW. In the next PSDP project the solar cell production capacity will further be enhanced to 500 kW annually to meet the growing demand of solar energy in the remote/rural area. The council is also establishing renewable Testing Laboratories at par with international standards through Government PSDP projects. These laboratories will test renewable energy based commercial products in line with ISO/IEC standards. During the last 3 years, 134 PV system of 26.5 kW capacity have been installed by PCRET electrifying 124 houses, schools and community centers. 3000 solar lanterns have been designed, developed and fabricated by PCRET, which are being disseminated to rural areas for popularization [66,76].

A number of solar thermal appliances including, solar water heaters, solar fruit and vegetable dryers, solar water distillation stills, solar room heating system, and solar cookers have been developed/fabricated by PCRET for domestic and commercial purposes. Recently PCRET has designed and developed a solar hybrid dryer for dehydration of apricot on commercial basis. Under PSDP project PCRET designed, developed and installed 10 solar dryers having 500 kg capacities for drying of dates in Punjab. More than 500 solar cookers and 50 solar stills designed, locally fabricated and handed over to NGOs for dissemination and popularization. Research and Development work in the field of other solar thermal devices is in progress. PCRET has also designed and locally fabricated solar room heating systems installed at PCRET building [76].

PCRET designed and installed 10 community size solar dryers of 500 kg capacity in the date growing remote areas of Punjab (District Jhang, Multan, Muzaffargarh and D.G. Khan), Sindh (Sukkur and Khairpur), Balochistan (Turbat, Panjgoor), KPK (Dera Ismail Khan) for demonstration purpose. The dryers were fabricated from the local market. The project was based on community participation and cost sharing, basis. The community nominated two suitable persons who remained associated from the beginning to the end of the project for the purpose of on job training. Twenty-five tones of quality dates per year are produced from the project, generating Rs. 3.5 million revenue. The normal operation and maintenance, is the responsibility of the beneficiaries. However, PCRET technical assistance team is monitoring the performance of the community dryers, which are working satisfactorily [76]. The target set by the PCRET 2011–2020 for promotion and dissimilation of solar energy in country are given in Table 5.

Table 5
Target set by PCRET from 2011 to 2020.

Type	Present status	Target 2011–2015	Target 2016–2020
Solar water heaters manufacturing through private sector with PCRET technical services	Designed and developed 05 different models of SWH for commercialization	10,000 units (125–260 l each)	25,000 units 125–260 l/day
Solar dryers manufacturing through private sector with PCRET technical services	Designed and developed 03 different models of 20,100 and 500 kg capacities	50,000 units	100,000 units
Solar cooker manufacturing through private sector with PCRET technical services	Designed and developed box and dish type solar cookers for commercialization	100,000 units	200,000 units
PV modules production manufacturing through private sector with PCRET technical services	Developed solar cell production capacities up to pilot scale	5 MW	20 MW
Wind turbines 100% subsidy	155 units of 0.5–10 kW capacity electrifying 1600 houses	1000 units 10 MW electrifying 50,000 houses	1000 nos. 10 MW electrifying 50,000 houses

Table 6
Details and location of manufacturers of solar geysers and solar lights in Pakistan.

Manufacturer	Location and other details	Manufacturer	Location and other details
1. Adaptive Technologies	Suit #3, 4th Floor, Dean Arcade, Block 8, Clifton Karachi Price: Rs. 25,000 (capacity 135 l)	2. Solar Tec.	283, Gulshan Block, Allama Iqbal Town, Lahore Price: Rs. 20,000 (capacity 100 l)
3. Asjid Energy Systems	6 Fazl-e-Qadir Road, Sialkot Cantt Price: Rs. 20,000 (capacity 90 l)	4. White Bear Solar Energy	F-8, Islamabad Price: Rs. 20,000 (capacity 100 l)
5. Attock Refinery Limited	Morgah, Rawalpindi Price: Rs. 45,000 (capacity 300 l)	6. NDI Corporation	1st Floor, Suite 7, Marble Plaza, Opp (Gas Ways CNG). I-9 Markaz, Islamabad
7. Ghulam Sabir & Co. (Solar Geysers)	Azharabad, GT Road, Turnol, Islamabad. Price: Rs. 20,000 (capacity 135 l minimum)	8. Consultronix (Pvt.) Ltd.	House No. 255, F-11/2, Margalla Road, Islamabad
9. Integrated Sustainable Technology (Firex Solar)	Plot No. 33, Street No. 10, I-9/2, Islamabad Price: Rs. 40,000 (capacity 200 l)	10. Control Systems Engineering	180/B, Ahmed Block, New Garden Town, Lahore
11. MEFT Private Limited	65, Gomal Road, E-7, Islamabad Price: Rs. 25,000 (capacity 150 l)	12. High noon International (Pvt.) Ltd.	134 Hali Road, Westridge-I, Peshawar Road Rawalpindi; Lahore Office: 11-Ross Residencia, 1-New, Campus Road, Canal Bank, Lahore
13. Renewable Energy Sources & Technologies (REST)	Apartment No. 8, Yasmeen Plaza, G-8 Markaz, Islamabad Price: Rs. 18,000 (capacity 100 l)	14. THRUST (SMC_PVT) Limited	Office #4, 1st Floor, Capital Trade Center, F-10 Markaz, Islamabad
15. Rockwell Solar Industries	House No. 9, Block No. T, Gulburg II, Lahore. Price: Rs. 30,000 (capacity 130 l)	16. Sun Techniques	B-25, Tatari Villas, Bath Island, Karachi
17. GET Technologies	E-149, Qazi Plaza Walton Road, Lahore		

8.2. EME College of NUST (National University of Engineering and Technology), Islamabad

EME College is working on the research and developments of Renewable Energy Technologies. It has installed a solar water heater of 40-ton/day capacities at an industrial unit at Lahore, solar water pumping system and solar house electrifications of 450 villages in FATA has been initiated from May 2009. Similarly, 50 units of solar/wind hybrid water pumping system and house electrifications in Kharan District of Balochistan province are under progress. Twelve solar cookers and two solar dryers having capacity of 50 kg each at Bagh Azad Kashmir have been installed. The current research emphases are being made on bio-diesel extraction, energy efficient building designs and waste heat recovery in the foundries [76].

8.3. Comsats Institute of Information Technology (CIIT)

Physics Department of CIIT, Islamabad is working on Quantum dot solar cells, research is in the initial stage [76].

8.4. Alternative Energy Development Board

AEDB has executed and implemented solar energy demonstration project “100 Solar Homes per Province” in following villages [77].

1. Allah Baksh Bazar Dandar, District Kech, Balochistan.
2. Bharo Mal, District Thar, Sindh.
3. Janak, District Kohat, KPK.
4. Lakhi Bher, Distrcit D.G. Khan, Punjab.

Each of the 100 households in each village has been provided with 88-W Solar Panels, 4 LED lights, a 12-V DC fan and a TV socket. In addition, a Solar Disinfecting Unit and a Solar Cooker have also been provided to each household. The project is aimed to serve the following purposes [77]:

a) To increase awareness in the use of renewable energy.
b) To provide basic necessities of lighting to remote locations.
c) To establish a model project in order to ascertain maintainability and sustainability parameters.
d) To develop a commercial model to encourage the private sector for replication.
e) To develop a solar technological base.

8.5. Manufacturers of solar geysers and solar lights in Pakistan

Private are playing their roles in the popularization and upgrading of PV activities in the country. More than 16 vendors are currently importing solar water heaters and marketing them all over the country, Details and location of manufacturers of solar geysers and solar lights in Pakistan given in Table 6 [56]. A number

Table 7
Potential and status of renewable energy in Pakistan [79].

Resource	Potential	Status (2006)
Hydro	The total hydroelectric potential in the country has not been fully investigated, but conservatively estimated to be 45,000 MW. This consists of all sizes of hydropower plants, including storage-based and high-head schemes on mountainous streams in the north and low-head, run-of-the-river plants on rivers and canals in the southern plains.	Pakistan has an installed hydroelectric capacity of 5928 MW of large (>250 MW), 437 MW of medium (>50 MW and <250 MW), and 253 MW of small to micro (<50 MW) plants, mostly in the northern parts of the country. This amounts to 6608 MW of total capacity, or less than 15% of the identified potential.
Wind	Commercially exploitable wind resources exist in many parts, especially in southern Sindh and coastal Balochistan, with monthly average wind speeds exceeding 7–8 m/s at some sites along the Keti Bandar-Gharo corridor.	No commercial wind farms in operation. Some micro-wind turbines pilot tested for community use.
Solar: Photovoltaic (PV) and thermal	Much of Pakistan, especially Balochistan, Sindh, and southern Punjab, receives abundant solar irradiation on the order of over 2 MWh/m^2 and 3000 h of sunshine a year, which is at the highest end of global insolation averages.	Negligible use in niche applications. No significant marketing of rooftop PV or household and commercial thermal systems.
Biomass: Bagasse, rice husk, straw, dung, municipal solid waste, etc.	Pakistan's large agricultural and livestock sector produces copious amounts of biomass in the form of crop residues and animal waste, such as much of which is currently collected and used outside the commercial economy as unprocessed fuel for cooking and household heating. In addition, municipal solid waste produced by a large urban population is presently openly dumped, which could instead be disposed of in proper landfills or incinerated to produce useable methane gas or electricity.	Sugar mills in the country use bagasse for cogeneration purposes and have recently been allowed to sell surplus power to the grid up to a combined limit of 700 MW. No other significant commercial biomass-based technology is presently employed for energy production/use in the country beyond experimental deployment of biogas digesters, improved cookstoves, and other small-scale end-use applications. Use of biogas digesters in rural households, after a promising start, has stagnated due to withdrawal of external subsidies.

of companies are not only involved in trading PV products and appliances, but also in manufacturing different components of PV systems. They are selling PV modules, batteries, regulators, inverters, as well as practical low power gadgets for load shedding including PV lamps, battery chargers, garden lights, etc. [40,78]. Only GET technologies is marketing solar lights in Pakistan.

8.6. Current status of renewable energy resources in Pakistan

A brief summary of the available renewable energy potential in Pakistan is given in Table 7, which also describes the current status of its development in the country.

9. Conclusion

Solar PV power is a commercially available and reliable technology with a significant potential for long-term growth in nearly all world regions. At present, there is rapid development occurring both in the basic technology and the market strategy and prospects for rapid growth of solar power. This vast potential can also be exploited to produce electricity specifically for off-grid communities. In Pakistan, cheap labor and high levels of solar radiations country receives throughout the year make condition favorable for development and promotion of solar energy. Both conventional PV and concentrated solar thermal technologies have clear room for development in the country. The main attractiveness of the PV technology is low maintenance, and no pollution, which has positioned PV to be the preferred power technology for many remote applications. At present the largest market for PV in Pakistan has been for applications such as telecom power, railway network, cathodic protection of pipelines, and defense services. The potential applications solar thermal technologies in Pakistan includes cooking, heating and cooling of buildings, generation of high temperature steam, heating water for domestic and industrial applications, and drying agricultural products under controlled temperatures.

Solar thermal systems are particularly effective in industries that require water temperatures in the range 40–80 °C. In Pakistan textile industry is a major sector in which solar energy can be practically utilized. The textile industry is a key sector of Pakistan's economy but also one of the most energy intensive industries. High energy prices and the widening gap between demand and supply have a negative impact on the productivity and competitiveness of the country's industry. Water heating system as required for dying process is one of the major energy consuming areas in fossil fuel-run Pakistan's textile industry. Solar water heating technology is quite mature in Pakistan but its use has been quite limited so far mainly because of higher capital cost of solar water heater as compared with conventional ones operating on natural gas. With the electricity and natural gas prices registering sharp increases, the use of solar water heaters is bound to increase. The production and commercialization of such heaters has already been started in the private sector.

Likewise, the cost effective design of desalination solar can provide the rural communities an efficient way to convert the brackish water into potable water. Pakistan can take benefit from the Chinese experience in solar water pumping to improve pumping groundwater for both drinking purpose and for irrigation in arid zones.

A number of solar thermal appliances including solar cookers, solar water heaters, solar fruit and vegetable dryers, solar desalination stills and solar space heating system have been indigenously developed and locally fabricated by PCRET and sections of Pakistan Council of Scientific and Industrial Research (PCSIR), National University of Sciences and Technology (NUST), Commission on Science and Technology for Sustainable Development in the South (COMSATS), Ghulam Ishaq Khan Institute of Science and Technology (GIKI) and different departments of Engineering Universities, etc. Many NGOs are popularizing these devices in the country. Private are playing their roles in the popularization and upgrading of PV activities in the country.

However further efforts are required for the development of indigenous technology to reduces the cost on local production of silicon and other advancements that increase the energy generation per gram of silicon over the lifetime of devices while improving the performance and durability of PV modules. Likewise low-cost materials and manufacturing methods are required to realize a

solar thermal electric system. Promotion of solar energy for power generation will require financial support and incentives, facilitation of technology transfer, and a large-scale research and development programme. Long-term and balanced policy effort in the next decade will allow for optimal technology progress, cost reduction and ramp-up of industrial manufacturing of solar equipments for mass deployment.

The cost of electricity from solar PV technology can come down by initiative from government such as indigenization of the technology and giving duty relief on import of technology. Attempts have been made in Pakistan both at installing small-scale PV power generators and at creating an indigenous PV fabrication capability. However indigenous fabrication facility exists only at PCRET whose capabilities remain at pilot scale. Imported solar modules are available in the open market in Pakistan, but at exorbitant prices. Governments have to provide long-term targets and supporting policies to build confidence for investments in manufacturing capacity and deployment of PV systems.

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